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ORIGINAL ARTICLE

Deciphering transmissivity and hydraulic conductivity of the aquifer by vertical electrical sounding (VES) experiments in Northwest Bangladesh

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Abstract The vertical electrical soundings (VESs) are carried out in 24 selective locations of Chapai-Nawabganj area of northwest Bangladesh to determine the transmissivity and hydraulic conductivity of the aquifer. Initially, the transmissivity and hydraulic conductivity are determined from the pumping data of nearby available production wells. Afterwards, the T and K are correlated with geoelectrical resistance and the total resistivity of the aquifer. The present study deciphers the functional analogous relations of the geoelectrical resistance with the transmissivity and the total resistivity with the hydraulic conductivity of the aquifer in northwest Bangladesh. It has been shown that the given equations provide reasonable values of transmissivity and hydraulic conductivity where pumping test information is unavailable. It can be expected that the aquifer properties viz. transmissivity and hydraulic conductivity of geologically similar area can be determined with the help of the obtained equations by conducting VES experiments.

Keywords VES · Transmissivity · Hydraulic conductivity · Aquifer · Chapai-Nawabganj

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Introduction

Basic elements of groundwater investigation involve determination of transmissivity and storage coefficient of the aquifers along with the geometry of the water-bearing zone. Pumping test is one of the suitable means for computing reliable and representative values of the hydraulic characteristics in aquifers (Ayers 1989; Kruseman and de Ridder 1994). Pumping test is an expensive process and therefore, long duration pump test is rarely carried out in practice. Surface geoelectric measurements provide an alternative approach for the estimation of some of the aquifer properties (Ahamed and deMarsily 1987; Khan et al. 2002). Though the geoelectrical methods alone, even under favorable conditions, do not replace test drilling to ascertain groundwater condition, yet in many cases can reduce the number of test drillings by giving a better selection of test borehole locations (Yadav and Abolfazli 1998). In past three decades, several investigators have studied the relations between aquifer parameters and geoelectric properties (Ponzini et al. 1984; Kelly and Frohlich 1985; Onuoha and Mbazi 1988; Mbonu et al. 1991; Kalinski et al. 1993; Frohlich et al. 1996; Dasargues 1997; Singhal et al. 1998; Niwas and De Lima 2006; Shevnin et al. 2006; Batte et al. 2010; Egbai 2011; Ezeh 2011; Majumdar and Das 2011; Sikandar and Christen 2012; Asfahani 2012; Niwas and Celik 2012; Nwosu et al. 2013; Ugada et al. 2013). Batte et al. (2010) correlated geoelectric data with aquifer parameters to delineate the groundwater potential of hard rock terrain in central Uganda. Egbai (2011) used information from vertical electrical sounding (VES) for the determination of the transmissivity of aquifers in Anwai, Delta State of Nigeria. Majumdar and Das (2011) characterized and estimated aquifer properties from electrical sounding data in Sagar Island region in south 24 Parganas of West Bengal, India. Sikandar and Christen (2012) estimated hydraulic conductivity using geoelectrical method in alluvial aquifers of Pakistan. Asfahani (2012) derived transmissivity of Quaternary aquifer from vertical electrical sounding measurements in the semiarid Khanasser valley region of Syria. Niwas and Celik (2012) estimated porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near-surface geophysical methods. Ugada et al. (2013) determined aquifer hydraulic characteristics of Umuahia area from Dar Zarrouk parameters. Nwosu et al. (2013) measured the hydraulic properties of the aquiferous zones using geoelectrical method for the evaluation of groundwater potentials in the complex geological area of Imo state, Nigeria. In all the above studies, mathematical equations were developed to estimate hydraulic aquifer property from surface electrical measurements. All the studies suggested that estimation of hydraulic conductivity and transmissivity from surface resistivity measurements is feasible. However, these relationships are area-specific and have limited applications in other area (Purvance and Andricevic 2000a, b; Niwas and De Lima 2006).

Groundwater is a major component of people's livelihood and agro-based economy in Northwest Bangladesh (Shahid and Hazarika 2010). About 75 % water for irrigation in the region comes from groundwater (Shahid 2010). However, overexploitation of groundwater in recent years has caused the groundwater level falls to the extent of not getting fully replenished in the recharge season. Actions are necessary to regulate the abstraction of groundwater in the area for sustaining rechargeable groundwater aquifers (Shahid and Hazarika 2010). Cost-effective estimation of aquifer properties is essential for this purpose. Therefore, the present study is carried out to

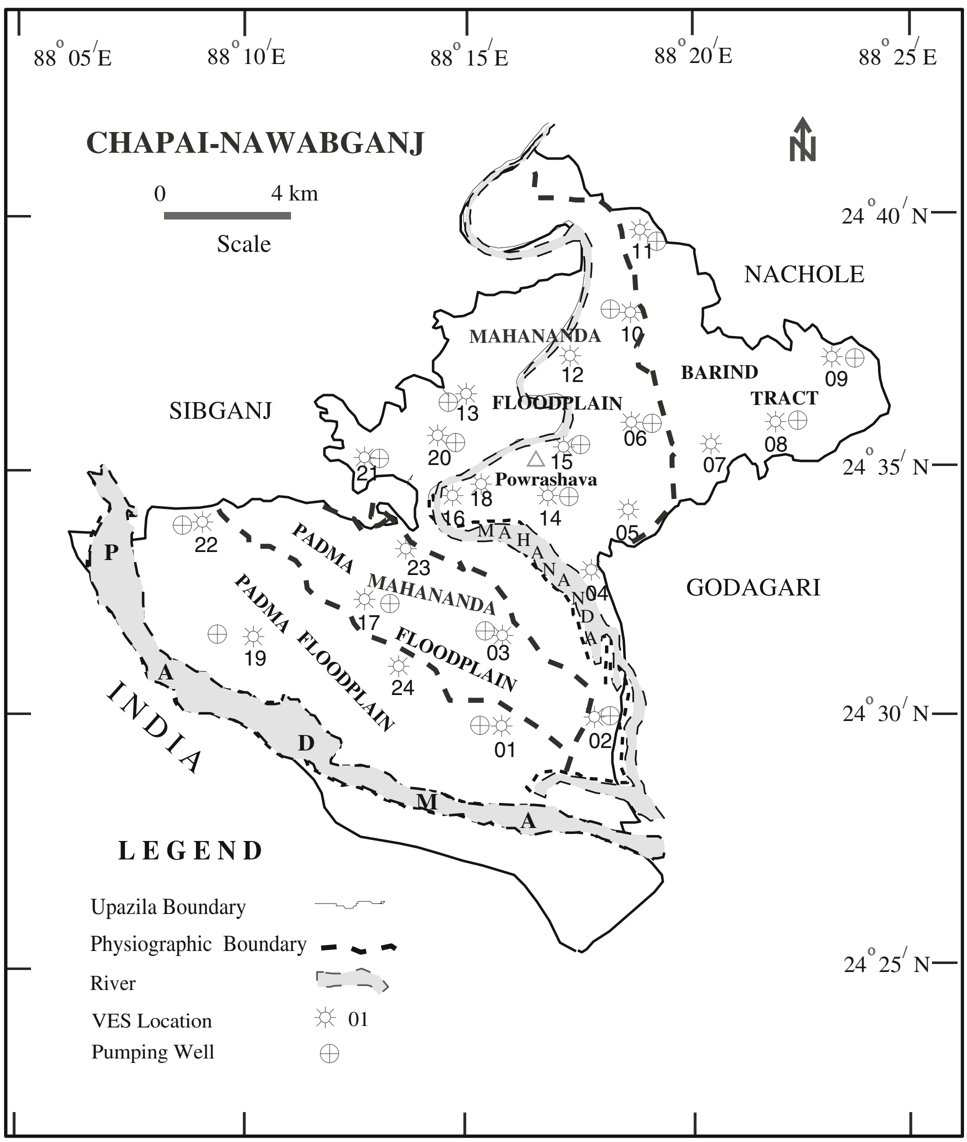

Fig. 1 Location map of study area

establish the physical relationship between aquifer properties and geoelectrical properties of the area obtained by VES experiments.

The VES experiments have been conducted in Chapai-Nawabganj area located in the northwestern part of Bangladesh. It lies between the geographical coordinates having latitude 24°25′N and 25°43′N and longitude 88°06′E and 88°25′E (Fig. 1). The area covers about 475 km^2 with population over 0.38 million, among which more than 60 percent depend directly or indirectly on agricultural work. The total cultivable land is about 340 km^2. More than 55 % of cultivated land requires irrigation, which totally fulfilled from groundwater.

Geology of the area

Geomorphology of the area can be broadly divided into two zones (Rashid 1991) viz. western floodplain (70 % of total area) and the northeastern Pleistocene Terrace (30 % of total area), which is also known as the Barind Tract (Morgan and McIntire 1959). The uplifted terraces of Pleistocene sediments of Barind Tracts are more strongly weathered than the surrounding alluvium. In the areas with alluvial, the Barind Tract sediments can be found at depths of the order of 150–200 m or more. Four distinct physiographic sub-divisions are identified in the present study area (Sattar 2005). These are Padma floodplain, Padma–Mahananda floodplain, Mahananda floodplain, and the Barind Tract. The Padma and the Mahananda are that two prominent rivers and control the overall hydrogeomorphological activity. The upper aquifers in the region are unconfined or semi-confined in nature. The thickness of the exploitable aquifer ranges from 10 to 40 m. Jahan et al. (1994) computed that the specific yield of the aquifer in the area varies from 8 to 32 % with a general decreasing trend from north toward central portion. The maximum depth to groundwater table from land surface varies from 7 to 30 m (Asaduzzaman and Rushton 2006). The topography of the area is mainly flat with an average elevation of 25 m above the mean sea level. There is a mild surface gradient toward southeast (Shahid and Hazarika 2010).

Materials and methods

Theoretical background

From well-known Darcy's law, the water discharge, Q (m^3/s), may be expressed in the form (Nath et al. 2000):

$$Q = KI'A \tag{1}$$

and the differential form of Ohm's law can be written as (Nath et al. 2000):

$$J = \sigma E \tag{2}$$

where K = hydraulic conductivity (m/day), I' = hydraulic gradient, A = area of cross-section perpendicular to the direction of flow, J = current density (A/m^2), σ = electrical conductivity (inverse of resistivity in a homogeneous, isotopic medium), and E = applied electrical field. These two fundamental laws of fluid flow and current flow may be utilized to find a probable relationship between electrical and hydraulic characters of the formation.

The geoelectrical resistivity, ρ, appears as the material specific constant of proportionality in the expression for the total resistivity (A) of the cylinder of length L and cross-sectional area D of uniform composition (Nath et al. 2000),

$$A = \rho L/D \tag{3}$$

The total resistivity can be obtained experimentally through Ohm's law, $R = V/I$, where V is the potential difference between the ends of the cylinder and I is the total current flowing through the cylinder. The resistivity of the material is an intrinsic property of the material, that can be calculated as the product of the apparent resistance $R_{app} = V/I$ and a geometric factor $K = A/L$ that carries information about geometry of the cylinder (Islami 2011).

Now if we consider a prism of unit cross-section, with thickness h and resistivity ρ, the resistance (R) normal to the face of the prism, and the conductance (S) parallel to the face of the prism can be given as (Patra and Nath 1999),

$$R = h\rho \tag{4}$$

and

$$S = \frac{h}{\rho} = h\sigma \tag{5}$$

This is when considering of a prism of aquifer material having unit cross-sectional area and thickness h. R and S are Dar Zarrouk parameters with R as transverse resistance and S as longitudinal conductance (Zohdy 1974 and 1975). The transmissivity T (the product of hydraulic conductivity and aquifer thickness) can be derived in terms of R and S as (Patra and Nath 1999),

$$T = K\sigma R \tag{6}$$

and

$$T = \left(\frac{K}{\sigma}\right) S \tag{7}$$

It has been observed (Niwas and Singhal 1981) that either of the two propositions, $K\sigma$ = constant or K/σ = constant could be true for an area under study, also valid for other areas with similar geological setting and water quality. Dasargues (1997) have used the overall resistivity of aquifer material to correlate it with hydraulic conductivity (K) using the relation (Patra and Nath 1999),

$$K \propto A \tag{8}$$

where

$$A = \sum \rho_i \tag{9}$$

where i represent different layers of aquifer. It is well-established fact that the variations in resistivity are due to the variations of geological formations with their characteristics' compositions.

Several investigations have been carried out in the past to relate aquifer parameters with geoelectric properties for different geological setup which have been discussed in detail in introduction section. In the present study, transverse resistance is correlated with aquifer transmissivity and the total resistivity is correlated with hydraulic conductivity to decipher the functional analogous relationships for Northwest Bangladesh.

Field survey and data processing

For the proposed study, 24 VES experiments were performed at pre-selected stations (Fig. 1) employing Schlumberger array. These stations were selected on the basis of reconnaissance survey, where emphasis was given on the proximity to the existing production wells. The field measurements were made with a minimum and maximum

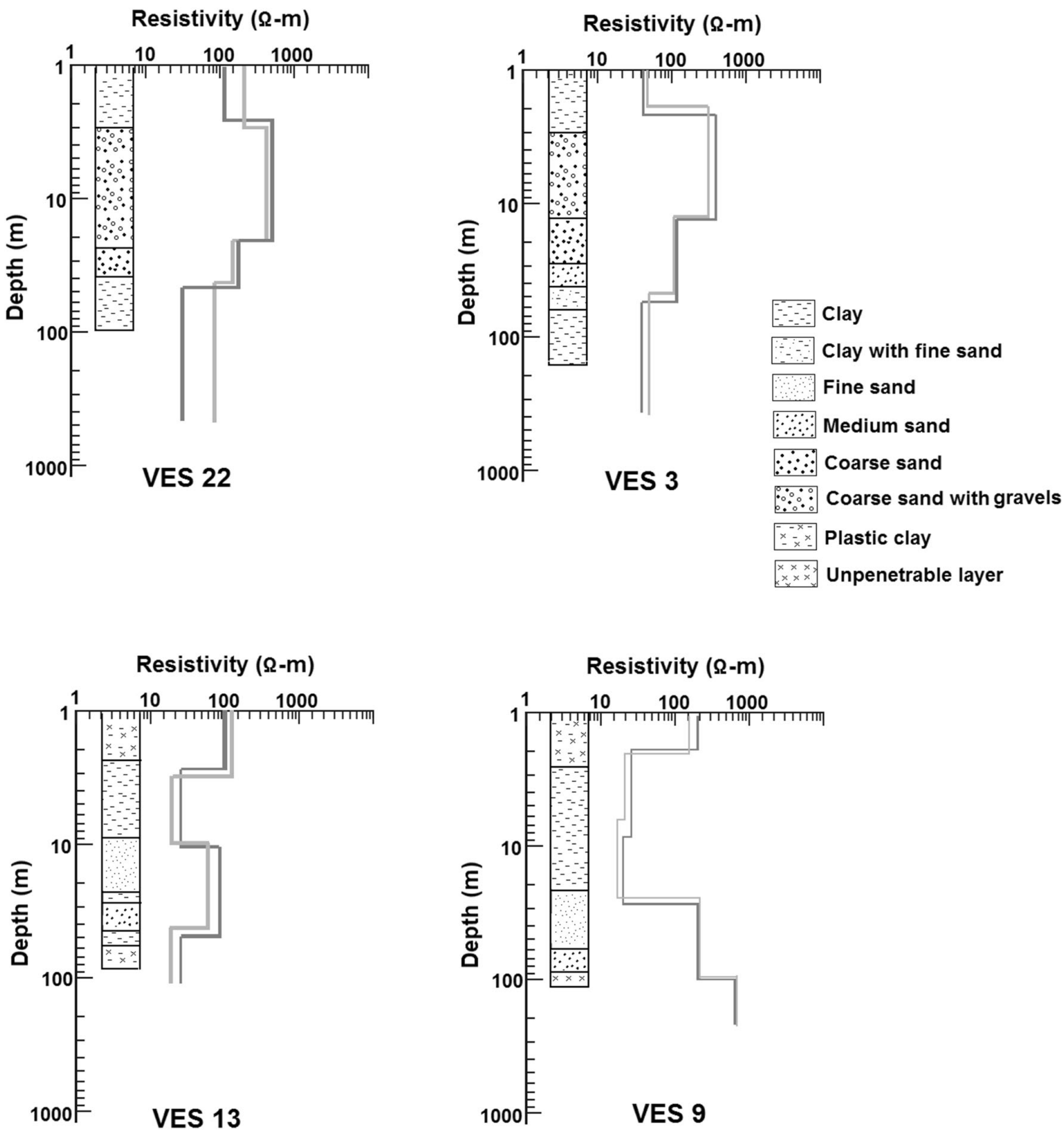

Fig. 2 Comparison of VES logs and lithologs in **a** Padma–Mahananda floodplain area; **b** Padma Floodplain; **c** Mahananda Floodplain; and **d** The Barind Tract

current electrode spacing (AB) of 400 and 1,000 m, respectively. The collected VES data were interpreted using both the multi-layer forward (Zohdy and Bisdorf 1989) and Inverse (Cooper 2001) methods. The intentions of the use of two models were to increase the acceptability of interpretation and hence furnish accurate information on groundwater-bearing formation underneath.

The pumping test data at 15 locations were collected from Barind Multi-purpose Development Authority (BMDA) and used for the estimation of aquifer hydraulic properties. Location of pumping test is also shown in Fig. 1. Same number is used in Fig. 1 to represent VES and pumping location. At each location, three-step pumping test for the period of 1,080 min, each step being of 360 min was conducted to study aquifer properties. The discharging rates of the steps were 4,893, 6,116 and 7,339 m^3/day, respectively. However, drawdown data were collected at regular time intervals. Pumping test data available in the study area were 'single-well test'. Considering the nature of data and their applicability to comply the different relevant equations, the Eden and Hazel (1973) method available in software StepMaster (version 2.0) was used to estimate transmissivity. The details of Eden and Hazel method can be found in Eden and Hazel (1973).

Result and discussions

Analysis of lithologs

On the basis of borehole information, the groundwater-bearing sedimentary sequences of the floodplain and Barind areas can be divided into several recognizable hydrostratigraphic units. The top clayey layer mainly consists of recent (floodplain) to older alluvium (Barind Tract) of Quaternary age. The textural characteristics of this unit are mainly clay, silt, and silty clay to very fine sand. Thickness of the zone also varies in accordance with its geomorphologic situation. In the floodplain area, the thickness ranges from 6 to 12 m. In and around the Barind region, thickness increases with the increase in elevation from 12 to 24 m.

The second layer is a composite aquifer. This is a common sandy unit of fine to medium-grained sand present just below the top layer in the floodplain area. Some times this zone is absent in the Barind region. Thickness of this zone varies from 5 to 15 m, and 3 to 10 m in the floodplain and Barind area, respectively.

The third layer is the main aquifer consisting of medium to coarse-grained sand, and coarse sand with gravels which serve as potential zones for groundwater storage, distribution and exploration. The main hydrogeological constrains of this porous zone is its uneven distribution below the composite aquifer layer. This zone is very thick (25–35 m) at few places around the floodplain area, and is relatively thin (10–15 m) in the Barind Tract. This indicates that the main water-bearing unit is gradually thinning from floodplain to the Barind area and is regarded as the ultimate

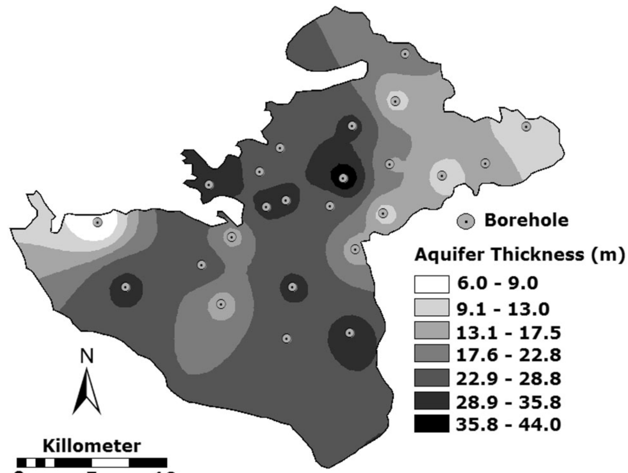

Fig. 3 Spatial distribution of aquifer thickness prepared from litho-log data

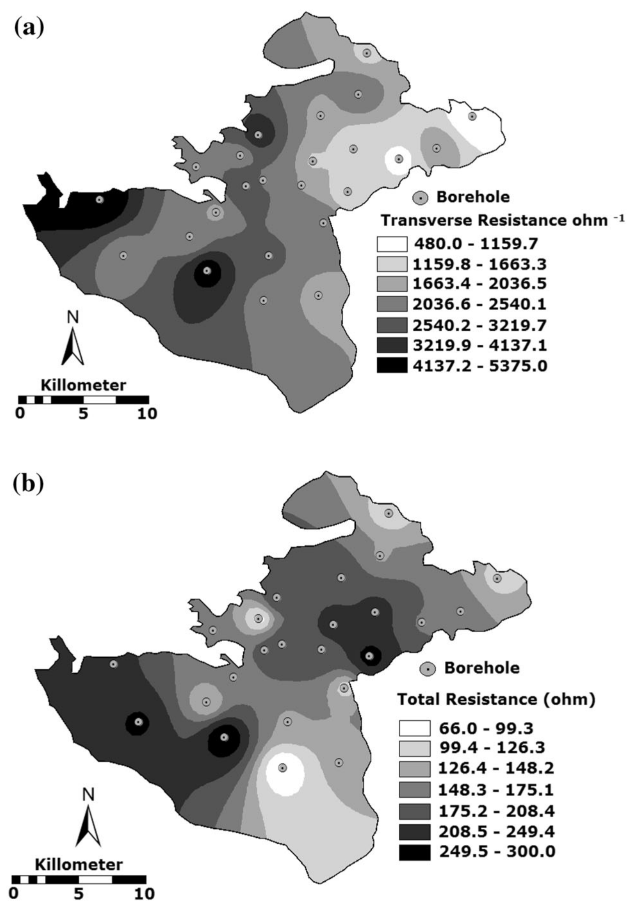

Fig. 4 Maps showing the spatial distribution of **a** transverse resistance; **b** total resistivity prepared from VES data

constrain of water scarcity of the Barind Tract. Considering the development potential of groundwater in the area of study, this zone can be considered as most productive zone at both floodplain and the Barind Tract.

The bottom layer in the region is commonly the Barind clay particularly at the Barind Tract. This clay is very hard and compact when it is dried. Its normal color is black but at places it varies from strong brown to very pale brown. Usually in the floodplain this lies just below main aquifer layer but at few places, especially in the Barind, it appears below the top aquitard layer or even very close to the surface and also to a considerable depth (40–45 m).

Water table in the area lies below the top aquiclude and hence developed a favorable confined condition for the main aquifer. The water in the aquifer is usually fresh.

Correlation between lithologs and VES logs

It is well recognized that the VES signature reflects the underground lithology up to which it reaches. The VES models have been compared with the available lithologs of the nearby location to observe the relation between them. The VES logs along with the nearest lithologs of different physiographic sub-divisions are presented in Fig. 2. It can be observed that in most cases the Forward models show better relation with the lithologs than those of the Inversion model. Vertical distributions of the VES logs are in good agreement with the lithologs having negligible discrepancy among them.

Aquifer thickness

Aquifer thicknesses from borehole data are interpolated using krigging method to prepare the map of aquifer thickness of the study area as shown in Fig. 3. Aquifer thickness is more than 10 m in most parts of the study area. The thickness is found to be less in Barind tract where it varies between 9.1 and 22.8 m. Aquifer thickness in other geomorphic region is more compared to Barind tract. In some parts of floodplain regions, aquifer thickness is found to be more than 35 m.

Table 1 Transmissivity of the aquifer determined from geoelectrical parameters

Physiographic sub-division	VES nos.	Transverse resistance (R) (ohm-m^2)	Transmissivity from pumping Test (T) (m^2/day)	Calculated transmissivity $T = 0.3079 \times R + 299.81$ (m^2/day)	Error (%)
Padma Floodplain	VES 01	2,250	912	993	9
	VES 19	2,025	1,124	923	18
	VES 22	5,375	1,820	1,955	7
	VES 24	4,846	x	1,792	[a]
Padma–Mahananda Floodplain	VES 03	2,660	938	1,119	19
	VES 17	1,548	662	776	17
	VES 23	1,903	x	886	[a]
Mahananda Floodplain	VES 02	1,800	781	854	9
	VES 06	960	764	595	22
	VES 10	2,560	932	1,088	17
	VES 12	1,947	x	899	[a]
	VES 13	4,014	1,846	1,536	17
	VES 14	2,020	810	922	14
	VES 15	1,565	627	782	24
	VES 16	3,600	x	1,408	[a]
	VES 18	2360	x	1,026	[a]
	VES 20	2,156	x	964	[a]
	VES 21	2,029	1,018	925	9
Barind Tract	VES 04	2,575	x	1,093	[a]
	VES 05	1,085	x	634	[a]
	VES 07	960	x	595	[a]
	VES 08	2,131	1,160	956	18
	VES 09	480	375	448	19
	VES 11	1,562	882	781	11

[a] Indicated the calculated values where there are no pumping test data

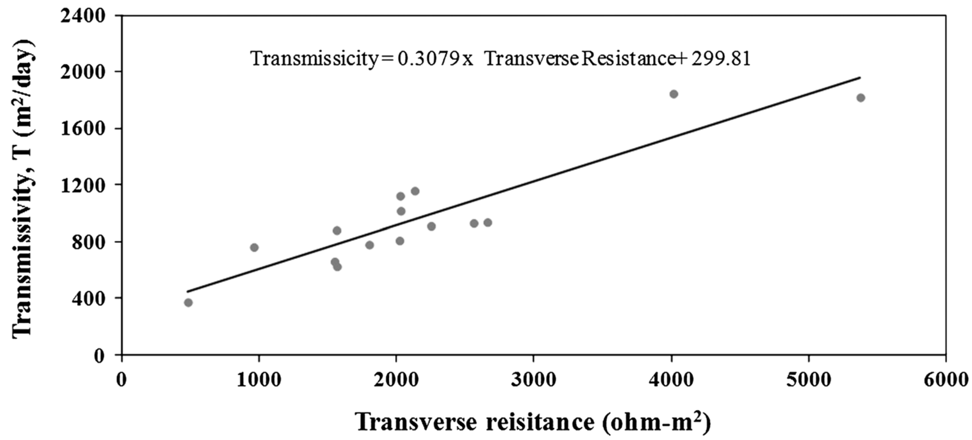

Fig. 5 Relation between the transverse resistance and transmissivity

Transverse resistance and total resistivity

Transverse resistance and total resistivity computed from VES data are interpolated to prepare the corresponding maps of the study area which are shown in Fig. 4a, b, respectively. The transverse resistance in the study area is found to vary between 480 and 5,375 ohm^{-1}. Overall, it is found to be less in Barind tract compared to other geomorphic regions. Total resistivity, on the other hand, is found to vary between 66 and 300 ohm in the study area.

Transmissivity from transverse resistance

In hydrogeological investigations, transverse resistance (R) has been found to be functionally analogous to transmissivity (T) (Cassiani and Medina 1997; Niwas and Singhal 1985). The value of transverse resistance computed from VES data and transmissivity of the aquifer computed from pumping test data at different sites near to the VES locations are summarized in Table 1. The transverse resistance R and the corresponding available transmissivity, T, from the pumping test data are plotted in Fig. 5. The scatter plot reveals a linear relationship between T and R in the form of:

$$T = 0.3079 \times R + 299.81. \tag{10}$$

The shape of the relation between aquifer properties and geophysical parameters can be linear or non-linear. Non-linearity arises due to heterogeneity or variations of lithological composition with directions. Alluvial aquifers are not free of clay. However, in only few cases, clay lenses are found within aquifer in the study area. Therefore, it is considered that the aquifer in the study area can be distinguished by low effect of clay content. Scatter plot of data shows linear relation between aquifer and geophysical parameters. When tried to fit with non-linear and linear equations, regression coefficient (r) is found to be higher for linear equation. Many other researchers also deduced linear relation between aquifer and geophysical parameters, considering geology and groundwater quality, remaining fairly constant within the area of interest (Niwas and Singhal 1981, 1985; Harb et al. 2010; Chachadi and Gawas 2012). Therefore, linear equations are derived to relate aquifer and geophysical parameters in the present study.

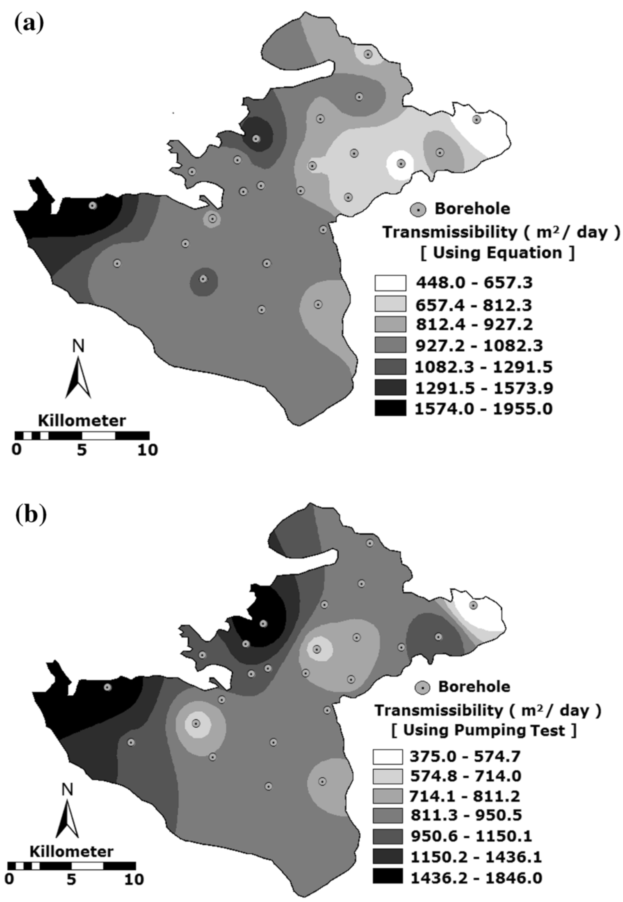

Fig. 6 Spatial distribution of aquifer transmissivity obtained from **a** transverse resistance; and **b** pumping test

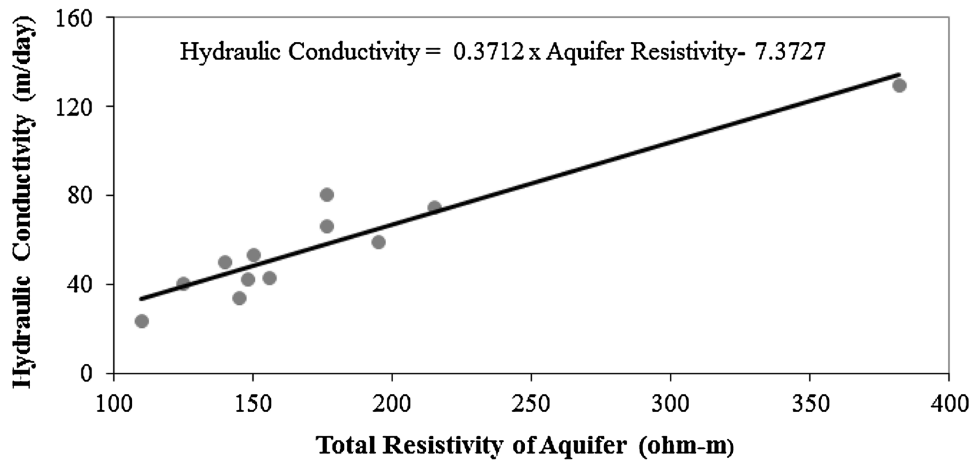

Fig. 7 Relation between the aquifer resistivity and hydraulic conductivity

Table 2 Hydraulic conductivity of the aquifer determined from geoelectrical parameters

Physiographic sub-division	VES nos.	Total resistivity of the aquifer (A) (ohm-m)	Hydraulic conductivity from pumping Test (K) (m/day)	Predicted hydraulic conductivity from the equation $K = 0.3712 \times A - 7.372$ (m/day)	Error (%)
Padma Floodplain	VES 01	66	34.4	31	10
	VES 19	255	69.6	75	8
	VES 22	215	80.2	66	18
	VES 24	300	x	85	[a]
Padma–Mahananda Floodplain	VES 03	143	60	49	18
	VES 17	114	33.5	42	26
	VES 23	163	x	54	[a]
Mahananda Floodplain	VES 02	132	45	46	3
	VES 06	225	67	68	1
	VES 10	145	43.4	49	14
	VES 12	195	x	61	[a]
	VES 13	212	85	65	24
	VES 14	200	52.9	62	18
	VES 15	229	57.8	69	19
	VES 16	185	x	59	[a]
	VES 18	205	x	63	[a]
	VES 20	85	x	36	[a]
	VES 21	154.5	43.6	52	18
Barind Tract	VES 04	115	x	42	[a]
	VES 05	272	x	79	[a]
	VES 07	172	x	56	[a]
	VES 08	155	50	52	4
	VES 09	120	42	44	4
	VES 11	110	46.9	41	12

[a] Indicated the calculated values where there are no pumping test data

The maps of aquifer transmissivity estimated from transverse resistance using Eq. (10) and that obtained from pumping test are shown in Fig. 6a, b, respectively. It can be seen from the maps that spatial distribution of transmissivity values calculated from transverse resistance matched well with that obtained through pumping test. It has also been found that the calculated T value in the VES locations, where pumping test data are not available (viz, VES locations 04, 05, 07, 12, 18, 20, 21 and 23) also well matched with the T of surrounding physiographic sub-

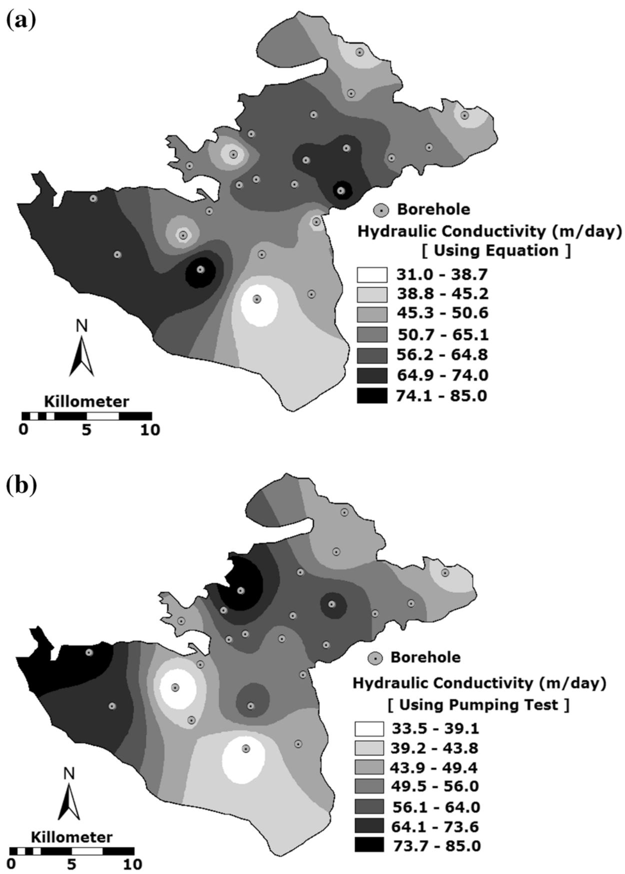

Fig. 8 Spatial distribution of hydraulic conductivity values obtained from **a** pumping test; and **b** total resistivity

divisions (Table 1). Therefore, it can be remarked that T (transmissivity) of the study area can be calculated from the VES data using Eq. 10.

Hydraulic conductivity from aquifer total resistivity

Aquifer total resistivity (A) estimated from VESs is correlated with the hydraulic conductivity values computed from the analysis of pumping test at 15 borehole locations near to the VES points. The plot of aquifer resistivity along abscissa and hydraulic conductivity along ordinate is presented in Fig. 7. This scatter plot also shows a linear relationship between K and A which can be written in the form:

$$K = 0.3712 \times A - 7.3727 \quad (11)$$

Hydraulic conductivity (K) estimated by pumping test and Eq. (11) are presented in Table 2. It is apparent from the Table 2 that values calculated by aforementioned equation give reasonable estimation of K for the respective regions which belong to different physiographic sub-divisions. The maps of aquifer hydraulic conductivity estimated from total resistivity using Eq. (11) and that obtained from pumping test are shown in Fig. 8a, b, respectively. It can be seen from the maps that spatial distribution of aquifer hydraulic conductivity values calculated from total resistivity match well with that obtained through pumping test.

Conclusion

In the complex floodplain–Barind geologic environment of the Chapai-Nawabganj area, the need for costly random drilling, resulting in dry holes or marginal production from wells can largely be eliminated by the judicious application of low-cost geoelectrical studies. Two inherent electrical properties of the earth materials viz. geoelectrical resistance (R) and the total resistivity (A) of the aquifer are easy to measure by conducting VES experiments. These two properties of aquifer materials have functionally analogous relation with the T and K, respectively. These are $T = 0.3079 \times R + 299.81$ and $K = 0.3712 \times A - 7.3727$. These equations were also authenticated by estimating aquifer parameters at some locations where pumping test information is not available. It is notwithstanding that the linear lines indicate a minor discrepancy over the transverse resistance and aquifer total resistivity. Therefore, it can be applied in geologically similar area where any information relating to pumping well or borehole available for the identification of the potential groundwater bearing horizon.

Analysis of lithological data shows that the second and the third lithological layers consists of medium to coarse-grained sand, and coarse sand with gravels serve as potential zones for groundwater storage, distribution and abstraction in the study area. The main water-bearing unit is gradually thinning from floodplain to the Barind area and is regarded as the ultimate constrain of water scarcity of the Barind Tract. The hydraulic conductivity is found to vary between 31 and 85 m/day, and the transmissivity to vary between 448 and 1,955 m^2/day in the study area. The transmissivity is found higher in the floodplain and less in Barind tract. The hydraulic properties of the aquifer reveal that floodplain regions are highly potential for groundwater abstraction.

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